RESEARCH ARTICLE OPEN ACCESS

Design and Simulation of Array of Rectangular Micro Cantilevers Piezoelectric Energy Harvester

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ABSTRACT
This paper presents the design, analysis and simulation of MEMS based array of bimorph rectangular microcantilever piezoelectric energy harvester structure with and without tip mass, to analyze their sensitivity. The microcantilever beams are made up of piezoelectric material and Aluminium as a substrate material. The analytical simulation of design is done by FEM (COMSOL Multiphysics). The simulation results of bimorph cantilever structure, applied force of 0.1 N and obtained end displacement and electric potential developed are given. The analytical model of the cantilever beam will be analyzed and the process of its construction will be discussed. The changes in the sensitivity of a cantilever beam with respect to change in its shape for the same applied force of 0.1N are denoted.
Keywords: Piezoelectric energy harvesting, FEM, Bimorph cantilever, COMSOL Multiphysics

I. INTRODUCTION

The motivation in this research field is due to the reduced power requirement of small electronic components, such as the wireless sensor networks used in passive and active monitoring applications[1-2]. The goal is to eliminate the need for battery replacement and disposal by enabling autonomous wireless electronic systems. Among the basic transduction mechanisms it can be used for vibration-to-electricity (electromagnetic, electrostatic, piezo electric and magnetostrictive) conversion methods as well as the use of electro active polymers; piezoelectric transduction has received the greatest attention due to the high-power density and ease of application of piezoelectric materials [3].

Most of the piezoelectric energy harvester structure uses the cantilever structure [4-5]. A cantilever is one which is fixed at one end and at the other end it is free to move when experiences some stress. A micro cantilever is a device that can be used as physical, chemical or biological sensor by detecting the changes in cantilever bending or vibrational frequency [6]. Shape of cantilever is shown in Figure 1.

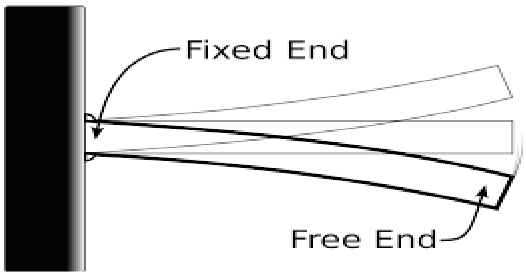

Figure 1 Cantilever structure

These microcantilevers generate a deflection at the free end when a force is applied. As their dimensions are in micrometers and the amount of stress that is applied is also very less, the deflection will also be in micrometers. Hence it becomes extremely difficult to measure the deflection when it is very less. So comparisons have been done by designing the microcantilevers with unimorph and bimorph configuration and estimating their deflection when the same amount of stress is applied. This helps us to find the shape of a microcantilever having maximum sensitivity. COMSOL Multiphysics, a commercial finite element analysis tool for MEMS was used to develop a finite element model of the piezoelectric energy harvester cantilever structure.

II. CANTILEVER CONFIGURATIONS

There are mainly two different type of cantilever configuration that can be used for energy harvesting: unimorph and bimorph configurations. In unimorph configuration piezoelectric element is deposited on single side of substrate layer. In terms of actual designs, bimorph cantilevers, where piezo element is deposited on both side of a substrate or to each other as shown in Figure 2, are also commonly utilized in order to improve the open-circuit voltage or output current (hence output power). It should be noted that in the case of the bimorph, a central electrode is needed, or the substrate for the bimorph (and for the unimorph) can be electrically conducting. In addition, multi-morph configurations containing several piezoelectric elements can be occasionally considered and element shapes can be tailored to optimize either output or efficiency [7]. A rectangular shape is the most typical and easy to fabricate; whereas triangular or trapezoidal shapes allow more even strain distribution and thus are capable of increasing output power and efficiency. The initial state of the cantilevers also has effect on the harvesting capability and working frequency range of piezoelectric energy harvesters. For instance, pre-stressed or pre-curved cantilevers are capable to enhance energy harvesting capability; and pre-stressed beams clamped on both sides can exhibit a wider range of responses to excitation frequencies.

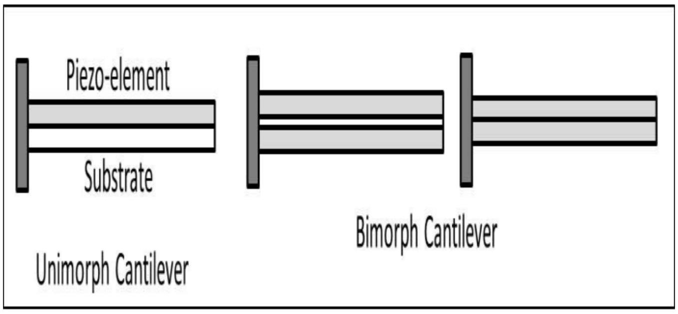

Figure 2 Unimorph and bimorph configuration of cantilever structure

III. PIEZOELECTRIC CANTILEVER THEORY (POLING AND ELECTRICAL CONNECTION OF BIMORPHS)

Unimorph and bimorph cantilevers are defined and distinguished in Figure.3. For a unimorph piezo-element with two layers of electrodes in parallel (like a capacitor), there is only one way to pole the material and connect the electrodes to external circuits if the cantilever is going to work in '31 mode' as depicted in Figure 3 (a). However, for a bimorph configuration, there are two different options to pole the two piezo-elements and connect the electrodes shown in Figure 3(b), 3 (c). Theoretically, the one poled in series and connected in parallel (called a parallel bimorph, Figure 3 (b) tends to double the output current or power coupled with proper loads compared to its unimorph counterpart, while the one poled in parallel and connected in series (called a series bimorph, Figure 3 (c) is able to double the open-circuit voltage [8].

However, strictly from the material's perspective, the important properties of piezoelectric materials for energy harvesting applications include piezoelectric strain constant d (induced polarization per unit stress applied, or induced strain per unit electric field applied), piezoelectric voltage constant g (induced electric field per unit stress applied), electromechanical coupling factor k (square root of the mechanical-electrical energy conversion efficiency), mechanical quality factor Q (degree of damping; lower value indicates higher damping), and dielectric constant ε (the ability of the material storing charge). The values of d, k, and ε for piezoelectric single crystals and ceramics are much higher than those of piezoelectric polymers. The g constants of the polymers are higher because of their much lower dielectric constants compared to those of the single crystals and ceramics as g=d/ε.

Since the goal of energy harvesting is to convert as much input mechanical energy into electric energy, when selecting a piezoelectric material for an energy harvesting application, one would want to choose a material with high electromechanical coupling factor k, as the square of k is the efficiency of this material converting the input mechanical energy to the output electric energy. A piezoelectric ceramic with high k's usually also has high d's because under static or quasi-static conditions (i.e. at frequencies much lower than the resonance frequency), k is directly related to d through elastic compliance and permittivity of the material [9]. For example, for a piezoelectric ceramic plate poled along its thickness direction, the planar-mode electromechanical coupling factor is in equation (1)

$$k^2_{31} = \frac{d^2_{31}}{s^E_{11}\varepsilon^T_{33}} \qquad (1)$$

where d_{31} is the piezoelectric strain constant (induced polarization in the "3" direction per unit stress applied in "1" direction), s^E_{11} is the elastic compliance and ε^T_{33} is the permittivity under constant stress.

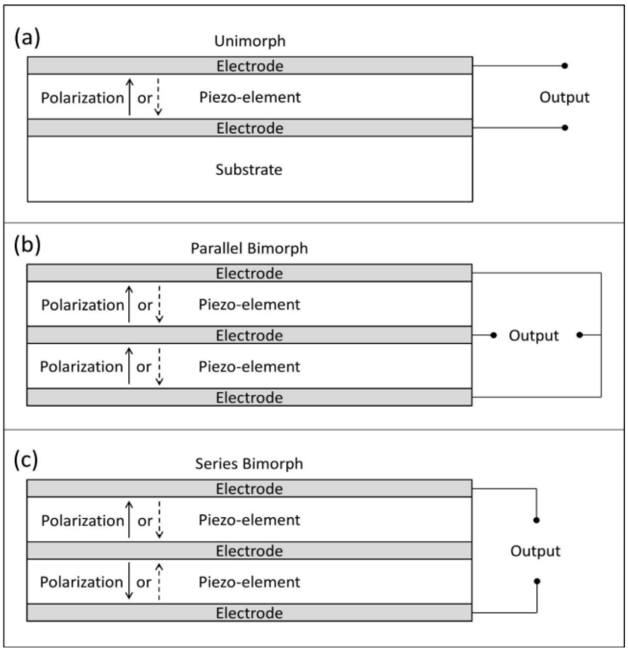

Figure 3 Schematics of poling and connecting methods (side-view): (a) unimorph; (b) bimorph poled in series, connected in parallel; (c) poled in parallel, connected in series

IV. CANTILEVER VIBRATION THEORY

Piezoelectric materials produce electrical charge when it is mechanically deformed; The IEEE standard on piezoelectricity gives different forms of piezoelectric constitutive equations [10-11]. The form used here is strain-charge form, and the equations are as follows:

$$S = s^E T + d\bar{E} \quad (2)$$

$$D = dT + \varepsilon^T \bar{E} \quad (3)$$

s : Mechanical strain.
S^E : Elastic compliance tensor (Pa^{-1})
T : Mechanical stress vector (Nm^{-2})
$\bar{E}$: Electric field vector (Vm^{-1})
D : Electrical displacement (Cm^{-2})
ε^T : Dielectric permittivity tensor (Fm^{-1})
d_{ij} : Electro-mechanical coupling factor (CN^{-1}), where i be polarization direction (usually 3) and j be strain direction.

Typically, two different modes can be used in the design of a piezoelectric harvester: longitudinal and transversal mode. The former is longitudinal mode (d_{31}) where the polarization of the beam is laterally developed in the deposited film. The commonly used is transversal mode (d_{33}) where the polarization of the beam is perpendicular to the deposited film.

Most important design parameter of a vibration energy harvesting device is the resonant frequency. Resonant frequency is calculated by using the given equation [4]

$$f_n = \frac{v_n^2}{2\Pi}\frac{1}{L^2}\sqrt{(D_p / m)} \quad (4)$$

where, $m = \rho_p t_p + \rho_s t_s$ (5)

$v_n = 1.875$ for first mode

m is the mass per unit area.

The bending modulus (D_P) is a function of Young's modulus and thickness and is expressed by

$$D_P = \frac{E_P^2 t_p^4 + E_s^2 t_s^4 + 2E_S E_p t_p t_s (2t_p^2 + 2t_s^2 + 3t_p t_s)}{12(E_P t_p + E_S t_s)} \quad (6)$$

Hence the variation of resonant frequency is

$$fn \propto \frac{1}{L^2}\sqrt{t_p}\sqrt{t_s} \quad (7)$$

Cantilever oscillates when placed in vibrating environment. The oscillations attain maximum peak value when vibration frequency of the environment matches the resonance frequency of the cantilever structure, and damps out dramatically for other frequencies [8]. Most of vibration source present in the environment have frequency in the range of 50-200 Hz, the proof mass lowers the resonance frequency of the cantilever by order of few Hz, which is generally the order of frequency of vibration present in the nature. Proof mass also increases the amount of deflection, hence increasing the stress at the fixed end due to which charge is generated in the cantilever structure. Electrical output voltage is highest when stress is maximum, which is at the resonance frequency. Dimensions of the model of cantilever are given below in Table 1. Figure 1.4 given below show the dimensions of cantilever structure.

Table 1: Dimensions of cantilever structure

Symbol	Description	Value
L_b	Beam length	75 mm
W_b	Beam width	36 mm
t_p	Thickness of piezoelectric material	0.4 mm
t_s	Thickness of substrate material	0.8 mm
t_m	Thickness of mass structure	5 mm
L_m	Length of mass	5 mm
ρ_s	Density of piezoelectric material	7500 kg/m3
ρ_p	Density of substrate material	7850 kg/m3
E_P	Young's modulus of piezoelectric material	64 Gpa
E_s	Young's modulus of substrate material	200 Gpa

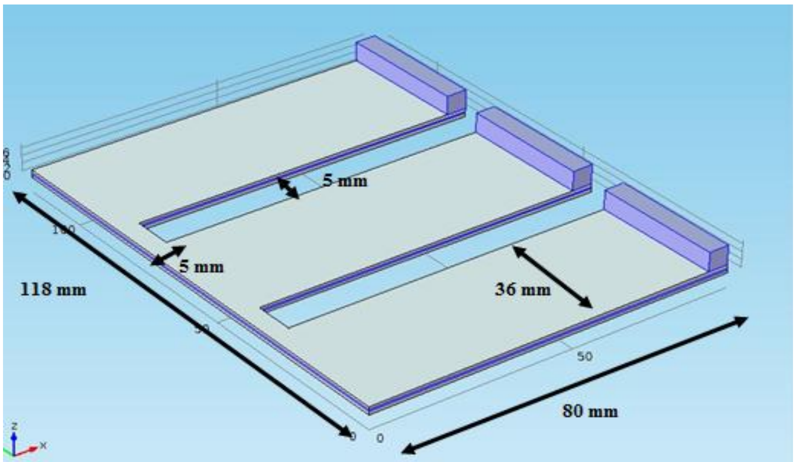

Figure 4 Dimension of cantilever structure

V. COMSOL MULTIPHYSICS TOOL

Piezoelectric energy harvesters with different structures are designed and simulated using COMSOL multiphysics tool. In which piezoelectric device module in 3D configuration is selected .The goal is to study the deformation and generated voltage with various cantilever structure.

The structures are composed of two or three sub domain with tip mass or without tip mass .Cantilever structure was simulated such that fixed constraint applied at the vertical faces of the cantilever structure means one end of the cantilever fixed and other end free to vibrate. Applying floating potential at the upper face and ground the lower face while all other faces are at zero charge constraint of piezoelectric layer, hence d_{31} mode is selected. At the cantilever structure body load of 0.1 N is applied. Now mesh the model in which geometry of the structure is divided into group of simpler finite element bricks and presented to the finite element solver.

VI. SIMULATION RESULTS OF ARRAY OF CANTILEVER STRUCTURE

Here array of rectangular cantilever structure have been simulated in the form of unimorph, bimorph and bimorph with tip mass. In simulation result, analyze the sensitivity of these cantilever structures with same applied body load of 0.1N.

6.1 Eigen Frequency Analysis

Eigen frequency analysis was conducted to obtain the resonance frequency of piezoelectric device. Knowledge of the resonance frequency is essential, since at resonant frequency piezoelectric harvester will give optimum output with highest possible energy conversion efficiency. After simulation it is analyzed that resonance frequency decrease with applied tip mass at the cantilever structure. Figure 5 given below shows maximum displacement of 0.459 mm at the free end of cantilever when body load of 0.1 N is applied on the single bimorph cantilever structure with tip mass and Figure 6 given below, shows maximum voltage of 4.23 V at Eigen frequency of 86.31 Hz.

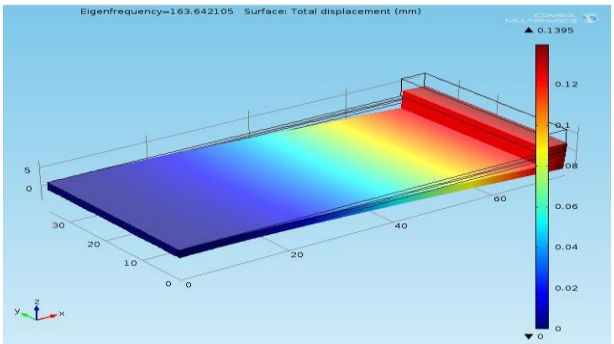

Figure 5 Displacement of rectangular cantilever structure with tip mass

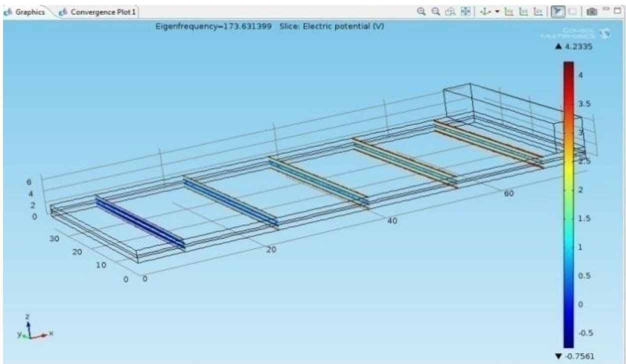

Figure 6 Voltage of rectangular cantilever structure with tip mass

Now the array of three rectangular cantilever structures has been simulated in the form of unimorph, bimorph and bimorph with tip mass and analyzed their sensitivity. Figure 7- 9 given below, shows maximum displacement at the free end of cantilever when body load of 0.1 N is applied on the unimorph, bimorph and bimorph with tip mass of the cantilever structure.

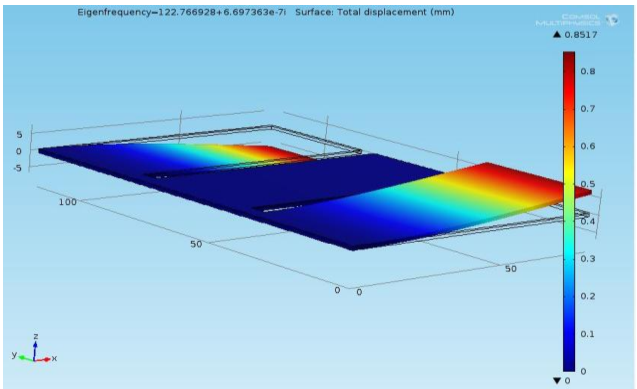

Figure 7 Displacement of array of unimorph rectangular cantilever structure

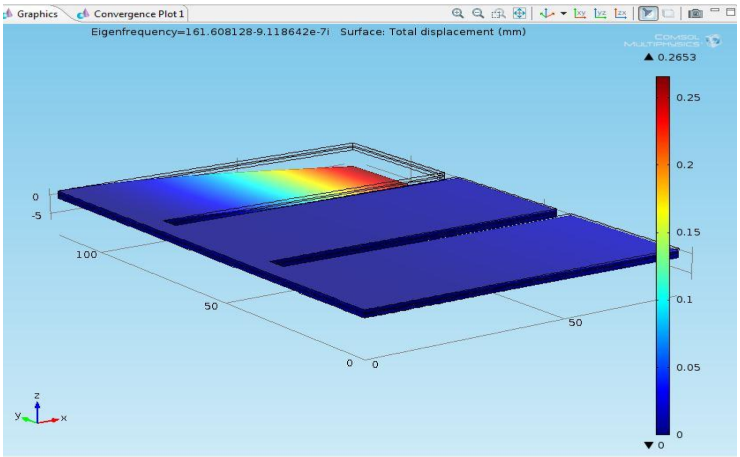

Figure 8 Displacement of array of bimorph rectangular cantilever structure

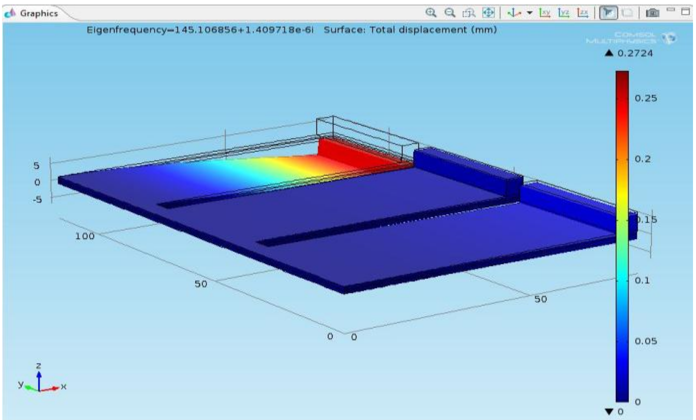

Figure 9 Displacement of array of bimorph rectangular cantilever structure with tip mass

Table 2: Displacement, Voltage and Eigen frequency of cantilever structure

	Array of unimorph rectangular cantilever	Array of bimorph rectangular cantilever	Array of bimorph rectangular cantilever with tip mass
Eigen frequency(Hz)	122.76	161.60	145.10
Displacement (mm)	0.851	0.26	0.27
Voltage (Volts)	9.9	11.36	11.37

Fig. 10-12 given below shows maximum voltage of cantilever when body load of 0.1 N is applied on the unimorph, bimorph and bimorph with tip mass of a cantilever structure

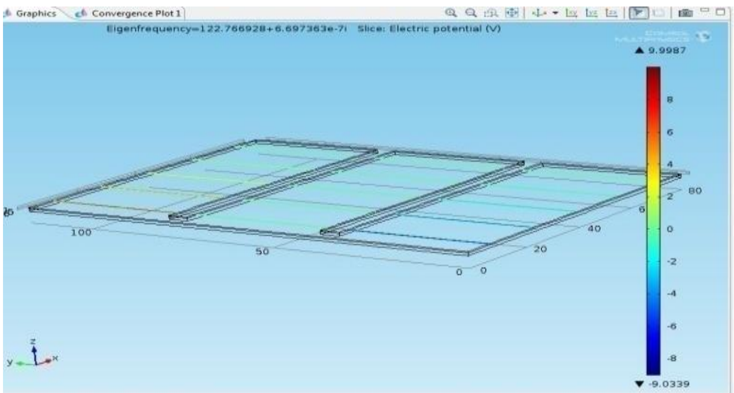

Figure 10 Voltage of array of unimorph rectangular cantilever structure

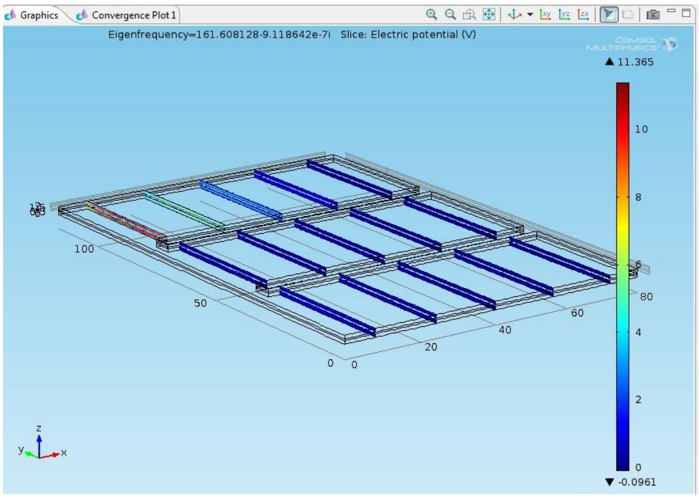

Figure 11 Voltage of array of bimorph rectangular cantilever structure

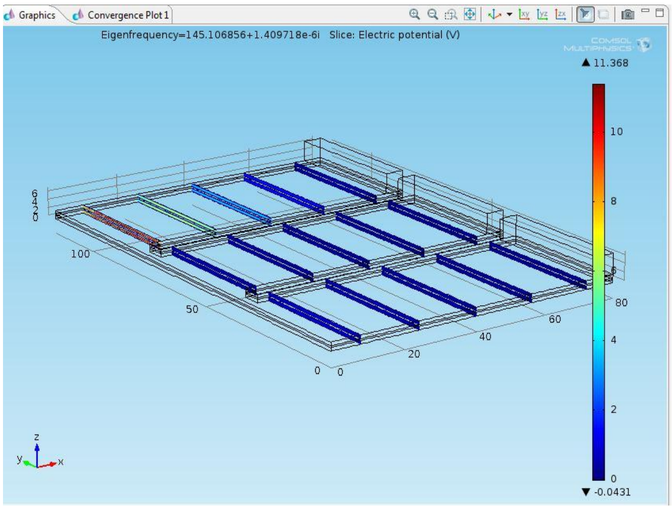

Figure 12 Voltage of array of bimorph rectangular cantilever structure with tip mass

In the simulation of array of rectangular cantilever structure with tip mass, we analyzed that when length of cantilever structure increases then frequencies of the structure decreases and voltage increases. Figure13 and Figure 14 shown below gives the length vs. frequency and length vs. voltage of cantilever structure respectively.

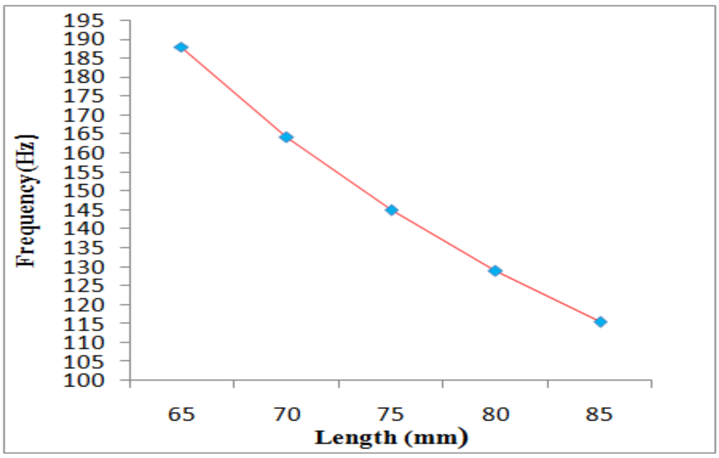

Figure 13 Frequency vs. beam length

In the simulation of array of rectangular cantilever structure with tip mass, we analyzed that when spacing between the cantilever increases (5 mm, 10 mm, 15 mm, 20 mm, 25 mm), width of each cantilever decreases, hence, the frequency of cantilever structure increases and its voltage decreases. Figure 15 and Figure 16 shown below gives the width vs. frequency and width vs. voltage of cantilever structure respectively.

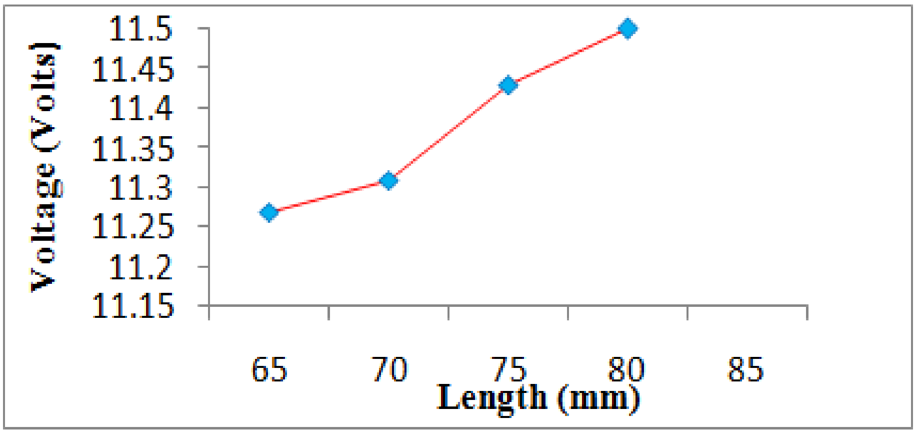

Figure 14 Voltage versus beam length

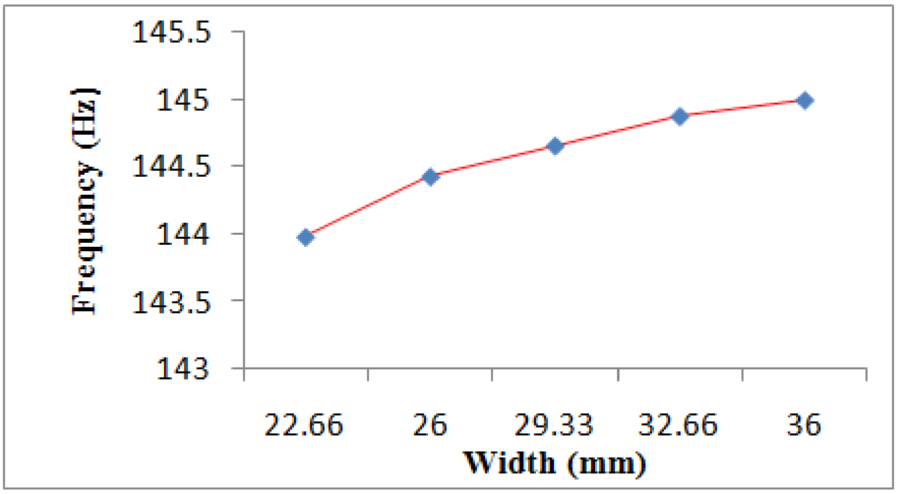

Figure 15 Frequency vs. beam width

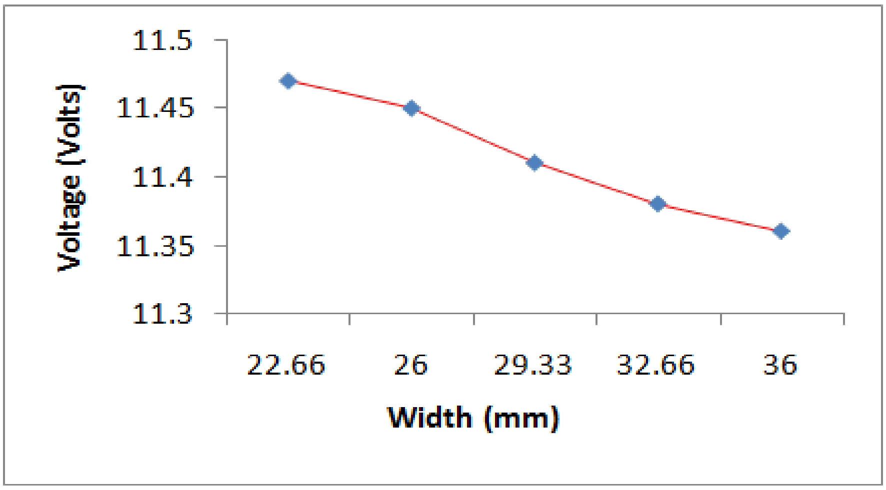

Figure 16 Voltage vs. beam width

VII. CONCLUSION

In this paper piezoelectric cantilever energy harvester with dimensions 75 mm x 36 mm x 0.4 mm is designed and simulated using COMSOL Multiphysics. The simulation results such as Eigen frequency, displacement and voltage sensitivity are analyzed for single and array of rectangular cantilever structures. It is analyzed that all cantilever structure have operated at resonance frequency between 100 to 200Hz and array of rectangular bimorph cantilever structure with tip mass have lower resonance frequency such as 145.40 Hz. Array of rectangular bimorph cantilever structure with tip mass give maximum output voltage 11.37 V with applied force of 0.1N at resonance frequency of 145.40 Hz. The simulations are carried out to predict the output voltage (V) with different length and width of the cantilever structure. Hence for energy harvesting array of rectangular bimorph cantilever structure with tip mass by using PZT (5H) piezoelectric material is best design.

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